A Novel Mapping Strategy of Repetitive Patterns in Consecutive Recordings to Localize Atrial Fibrillation Sources: an In-Silico Study

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Abstract

In some patients with persistent atrial fibrillation (AF), localized functional mechanisms may sustain AF and thus represent ablation targets. We propose a novel mapping strategy to locate AF sources by combining repetitive patterns from consecutive high-density mapping recordings. The algorithm moves the catheter iteratively upstream of the main repetitive conduction direction to identify an AF source either by direct classification of local activation patterns or by encircling it. We tested the performance and robustness of this approach in two groups of detailed AF simulations, without and with severe structural remodeling (N=20 per group, 20 starting positions per simulation), using a 4x4 grid mapping catheter (3mm spacing). Structural remodeling led to more simultaneous sources (median [IQR], 2 [1; 3] vs 3 [2; 5], $p < 0.001$) that meandered in larger areas (127.5 [82.0; 216.0] vs 188.0 [121.2; 305.5] mm^2, $p < 0.05$). The mapping approach localized a source in 6 [4; 9] vs. 5 [5; 8] steps for the groups without and with structural remodeling ($p < 0.001$), with an accuracy of 11 [7; 16] vs 9 [6; 14] mm ($p = 0.046$). Sources were localized by encircling in 62.6% vs. 41.4% of the detection in both groups, respectively. The proposed mapping strategy detected AF sources accurately within a few steps, even in complex AF substrates, with a substantial contribution of encircling to detect sources.

1. Introduction

Despite advancements in ablation therapy for atrial fibrillation (AF), success rates and long-term outcomes remain suboptimal [1]. While pulmonary vein isolation is effective for paroxysmal patients, the outcomes are worse for persistent AF cases with complex substrate due to extensive electrophysiological and structural remodeling. However, some persistent AF patients may have localized sources of AF outside the pulmonary veins, which can be relevant ablation targets.

Functional ablation strategies targeting such sources are not yet widely accepted in clinical practice due to conflicting results of clinical trials [2]. While the limited success of these techniques may be in part related to patient selection, another explanation is the potential mismatch between the dynamics of AF sources and the type of catheters currently used to localize them. Catheters with high spatial coverage but low spatial resolution, may incorrectly identify or miss sources such as reentries [3]. High-density mapping catheters can capture local conduction patterns in more detail. However, because of their limited field of view they require sequential maps, which reduces their capability to detect meandering or shifting sources. [3].

In this study, we propose a novel mapping strategy to guide high-density catheters towards AF sources, identifying them even when their conduction patterns are not visible at a single site. Our approach combines repetitive patterns of activation from consecutive endocardial electrogram recordings to localize AF drivers. It defines an AF source as a region of the atria from which continuously or intermittently repetitive conduction patterns propagate to neighboring regions [4], thus encompassing multiple source types such as reentries, ectopic foci, and transmural breakthroughs [2]. We evaluated our approach in detailed AF simulations, assessing its robustness against increased AF complexity due to substrate remodeling.

2. Methods

The stepwise AF mapping approach to localize AF sources is outlined in Figure 1. Unipolar endocardial electrograms (EGMs) recorded with a high-density mapping catheter are used as input to a source localization and detection algorithm. Starting from a given initial location, the algorithm attempts to identify an AF source either by directly classifying local activation patterns or by encircling the region in which a source is present. When no source is located, the catheter is moved upstream from the main conduction direction of repetitive activations patterns on the EGMs. This procedure is repeated until a source is localized.

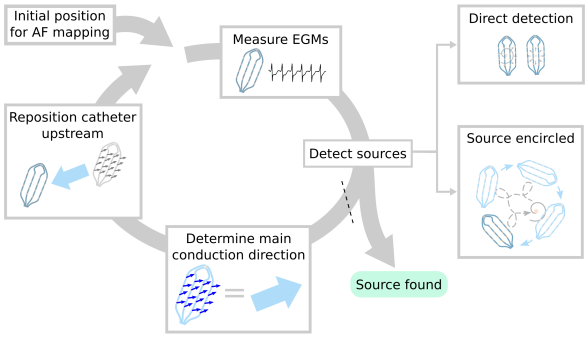

Figure 1. **Overview of the mapping approach.** EGMs are obtained sequentially during AF with a high-density mapping catheter. The catheter is moved against the main conduction direction of repetitive activation patterns until a source is detected by either classifying local activation patterns or by encircling it.

2.1. Repositioning the mapping catheter

To locate AF sources, repetitive activation patterns upstream of their main conduction direction are followed. Recurrence plots are used to detect intervals of repetitive activity, focusing the analysis on the most organized activity [5]. The main conduction direction is determined in repetitive intervals >3 average AF cycle lengths, and the catheter is sequentially moved upstream with a given step size. Downstream regions are marked as invalid for future catheter positions within a radius corresponding to the catheter size. If no repetitive interval is detected, the catheter is repositioned randomly 5 mm away from the previous position, with only the previously mapped region marked as invalid for future placements.

2.2. Detecting AF sources

We applied two strategies for detecting an AF source: direct detection and encircling. Direct detection means that the mapping catheter is placed directly on top of a source, and the source is observed within the catheter's field of view. Any algorithm can be used for this approach, depending on the catheter and targeted AF mechanism. On the other hand, encircling is useful for detecting less stable sources, such as meandering reentries [6]. The regions marked as invalid for future placements during the source tracking may enclose a region in the atria. If activation patterns propagate outside of this region, its center is marked as a potential AF source.

2.3. In-silico experimental setting

To develop and test the proposed mapping strategy, a highly detailed computer model of the human atria was utilized [7]. This model incorporates reentries and transmural breakthroughs, which are important mechanisms for AF maintenance. Two groups of AF simulations were created using this model, each representing different levels of structural remodeling in the atria. These changes in the atrial substrate can result in varying numbers of AF sources with different degrees of spatiotemporal stability.

The study involved two groups of simulations. The first group consisted of simulations on structurally normal atria, representing earlier stages of AF progression, such as in paroxysmal AF patients. The second group represented more persistent cases of AF, with a high degree of structural remodeling. In this group, 70% of the atrial surface was covered with random patches of endomysial fibrosis [8]. To initiate AF in both groups, pacing was incrementally increased from 280 to 124 ms from 20 selected locations. AF was then simulated for 30 seconds, and the EGMs were measured in 2.5s intervals ($fs = 1000$ Hz).

Mapping procedures were initiated from 20 distinct positions uniformly spaced along both atria, using a virtual high-density mapping catheter with a 4x4 electrode grid and 3 mm spacing to record unipolar EGMs sequentially, with 10 mm steps. The mapping was limited to the same atrium in which the initial position was located. Regions downstream of the main conduction direction within a 10 mm radius were marked as invalid for future placements. To identify sources directly, we utilized a classification method based on activation wavefronts [9], capable of detecting reentries and radial spread of activations.

The mapping strategy's performance was evaluated based on the number of steps and distance from the true source location obtained from transmembrane potentials [7]. Source detection methods (direct vs. encircling) were compared across simulation groups using Kruskal-Wallis tests (with Dunn's test as post-hoc) at $\alpha = 0.05$.

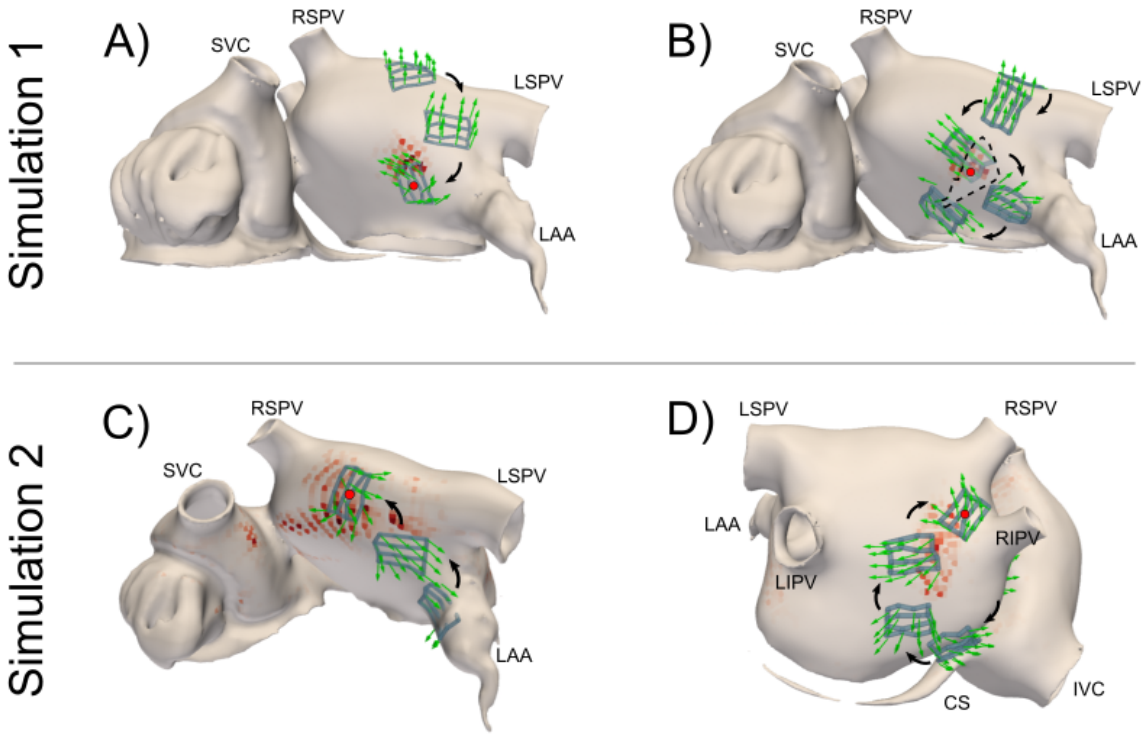

Figure 2. **Examples of mapping procedures in two simulations**. Sources were detected either locally (A, C, D) or by being encircled with subsequent catheter positions (B). Different starting positions may lead to different sources when multiple reentries were present (C vs. D).

3. Results

AF initiated in 35% vs. 55% of the simulations for the groups without and with severe remodeling, respectively. During sustained AF, the groups had 2 [1; 3] vs. 3 [2; 5] simultaneous reentries present ($p < 0.001$), which meandered in an area of 127.5 [82.0; 216.0] vs. 188.0 [121.2; 305.5] mm^2 ($p < 0.05$), indicating an increase in complexity with the remodeling.

Figure 2 shows examples of mapping procedures along with the distribution of reentries, for two simulations. In the first simulation, the source was found by direct classification of local conduction patterns in the first mapping procedure (Fig. 2A), but could only be identified by encircling it in a different procedure (Fig. 2B). In the second simulation, both sources were identified by placing the catheter directly on them, but different starting positions led to different sources (Fig. 2C and D).

In simulations without remodeling, sources were identified after 6 [4; 9] steps, with an accuracy of 11 [7; 16] mm when compared to the ground truth. In this group, 62.6% of the sources were detected through encircling by successive catheter positions. In the severely remodeled group, the sources were localized in 5 [3; 8] steps ($p < 0.001$ vs. non-remodeled group) with an accuracy of 9 [6; 14] mm ($p = 0.046$ vs. non-remodeled group). 41.4% of the sources in this group were detected by being encircled.

4. Discussion

This study describes a novel approach for atrial mapping to locate areas potentially driving AF, by using information about conduction directions on sequential high-density maps. We used an in-silico environment to test the approach to be able to validate the outputs against the known underlying conduction patterns. Our results demonstrate that repositioning the mapping catheter upstream of the conduction direction should lead to a potential AF source within a few steps. This source can be detected either locally or by being encircled by successive recording locations. The performance of this approach did not decrease with the progression of AF-related substrate remodeling.

Clinical trials attempting to ablate sources of AF have yielded conflicting outcomes, possibly due to technical limitations such as low-spatial resolution of mapping catheters or narrow field of view [2]. Our mapping approach attempts to overcome these limitations by suggesting an objective approach to sequential mapping of AF that takes into account the limitations of the field of view

and resolution of the catheters. High-density catheters provide detailed information with sufficient resolution to detect specific conduction patterns, such as reentries, when present in the field of view [3]. On the other hand, considering an encircled area as the position of a source provided benefits to their localization, enabling the algorithm to identify sources that meandered in areas larger than the electrode array.

Our results show that this technique is robust to an increase in AF complexity that could result from severe remodeling of the AF substrate. A higher number of simultaneous reentries led to their identification with fewer steps and lower error in the severe remodeling group, potentially due to the increased likelihood of placing the mapping catheter on a source. The higher number of simultaneous reentries also led to smaller areas influenced by each reentry, thus favoring the local detection of sources in this group.

Our method accurately identifies functional mechanisms in AF, but it does not determine the role of these sources to the maintenance of the arrhythmia. To determine their impact, future studies are necessary to determine the relevance of each individual source, either by ranking their importance for conduction during AF or by evaluating whether their ablation terminates AF conduction.

The information used for our mapping approach, such as activation times and conduction directions, can already be obtained from current mapping systems (e.g. Deno et al. [10]). This compatibility facilitates the application of the proposed approach in clinical practice by electrophysiologists aiming to identify functional mechanisms of AF.

5. Conclusion

Repositioning mapping catheters upstream the leading conduction direction and combining sequential recordings may increase the efficiency and accuracy of mapping procedures for the identification of AF sources. Encircling sources substantially contributed to their detection. The proposed algorithm successfully localizes AF drivers even in complex substrates of AF.

Acknowledgments

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